NUMERICAL INTEGRATION STUDY OF EARTH IMPACT BY METEOROIDS FROM THE 3:1 RESONANCE. G. W. Wetherill & J. E. Chambers*, DTM, Carnegie Institution of Washington, Washington, DC 20015-1305, USA (*Presently at the Armagh Observatory, Armagh, Northern Ireland).

Our understanding of the mechanisms by which meteorites and near-Earth asteroids are transferred from the asteroid belt to Earth has advanced considerably since Opik (1) showed that the conventional qualitative mechanisms for this transfer were grossly inadequate. It became evident that the most promising way to accomplish this was by the effect of resonances, particularly the ν_6 secular resonance (2,3) and the 3:1 Jovian commensurability resonance (4). Only recently, as a result of very fast integrators (5,6,7) and the availability of inexpensive fast workstations, has it become possible to obtain a sufficiently large sample of orbital evolutions to have statistical significance. In this way, *Gladman et al*. (8) and *Migliorini et al*. (9) have found that the time scale for loss of material from the Solar System by these resonances is considerably shorter than almost all of the cosmic ray exposure ages of ordinary chondrites.

The present investigation addresses this problem for bodies originating in the 3:1 resonance. The emphasis in this work is not so much on the short time scale for loss of bodies, already well established by the workers cited above, but by the quantity and orbital characteristics of the material that does strike the Earth despite the $\sim$ 2.5 m.y. time scale for loss of these bodies. In order to obtain useful sampling of these impact events, the orbital elements of grazing encounters within $<$ 20 Earth radii were interpreted as ‘‘surrogate" impact events, which could have been impacts but for very small differences in the orbital elements of the bodies. Following these sometimes multiple grazing encounters, the evolution of the bodies was continued until they were terminated by sun grazing, ejection beyond 40 AU or actual impact with a planet.

A program, based on the SWIFT programs, generously provided by H. Levison, was developed here. The MVS symplectic integrator was augmented by the use of a Bulirsch-Stoer program when test bodies pass within two Hill radii of a planet. The orbital evolutions of 258 test particles and the 8 larger planets were calculated in this way for up to 20 m.y. All but two of the bodies were lost before 20 m.y. Except for 40 bodies with initial semimajor axes at 2.49 or 2.51 AU, all the bodies initially had a = 2.50 AU. Eccentricities and inclinations were distributed between 0.01 and 0.20 and 2.5° and 12.5°. Three actual Earth impacts were found.

Fig. 1 shows that the distribution of eccentricity of the surrogate impacts fills essentially all of the allowed Earth-approaching $a - e$ space. However, much of this space corresponds to impacts at atmospheric entry velocities $>$ 20 km sec, for which the mass reaching the ground will be severely attenuated by mass loss (Fig. 2).

Fig. 3 shows that the perihelia of the impactors are also widely distributed. When bodies with entry velocities greater than 20 km/sec are removed (Fig. 4), the remaining bodies have a distribution of perihelion vs. a similar to those found for recovered fireballs and those inferred to be stony meteorites based on their atmospheric entry behavior (9), as shown in Fig. 5.

The distribution of impacts in one million year intervals is shown in Fig. 6. The initial decline in the impact rate is a consequence of the rapid loss of the bodies into the Sun, and to a lesser extent by ejection beyond 40 AU. However, the impact rate does not decline as rapidly as the number of bodies, because of the evolution of a few percent of the bodies into orbits with a $\lesssim$ 2 AU. This leads to a large number of impacts as a consequence of the long residence time of bodies in these orbits, together with their high impact probability resulting from their relatively low relative velocity and their perihelia near 1 AU.

In the case shown, the population of a $<$ 1.5 AU impact orbits is dominated by surrogates of two bodies, the more important of which became Earth-crossing with a $<$ 2 AU within $\sim$ 1/2 m.y. and remained in this small orbit until it really struck the Earth after 30.3 m.y. The peak in impact rate at 10 m.y. is an artifact of being dominated by two bodies, but if a larger sample were used, they could fill in the region in which cosmic ray exposure ages are usually located (5 -- 50 m.y.).

Even if a small number of unusually efficient Earth-impactors of this kind can provide objects with exposure ages in the usual range, the problem identified by Gladman of the paucity of impactors with short exposure ages remains. His suggestion that this may be a consequence of the material injected into the resonances being already small enough to permit prior 4π irradiation is at least qualitatively consistent with the concept that a large fraction of the parental material in the collision cascade is small enough to be irradiated throughout (10). Even when these questions are resolved, there remains the difficult problem of determining whether or not the 3:1 source provides enough mass to represent a major source of meteorites and near-Earth objects. The more we learn the more there remains to be learned.

References:

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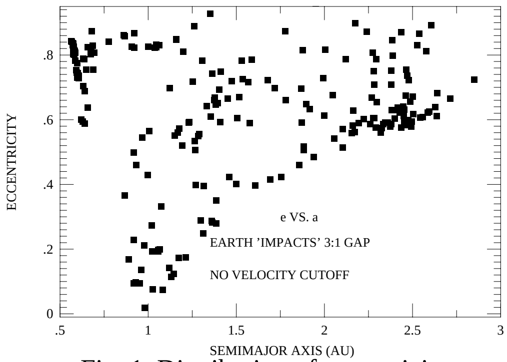

Fig. 1. Distribution of eccentricity vs. *a;* grazing encounters within 20 Earth radii.

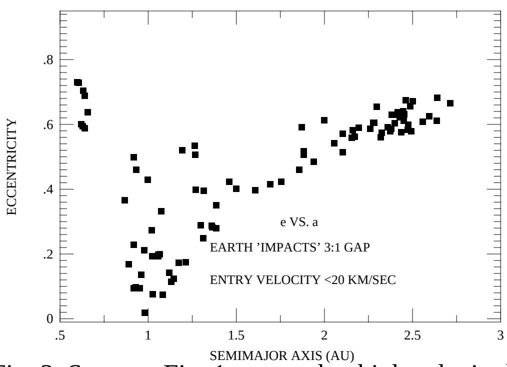

Fig. 2. Same as Fig. 1 except that high velocity bodies unlikely to survive atmospheric entry (20 km/sec) have been removed.

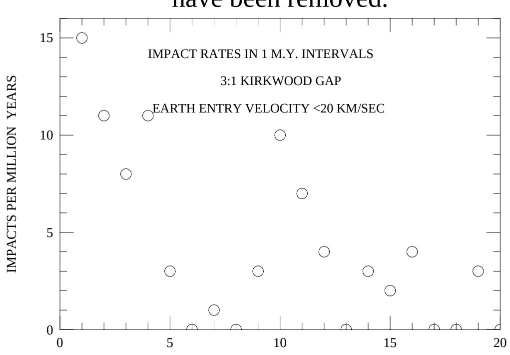

Fig. 3. Earth grazing impact rates for 1 m.y. time intervals.

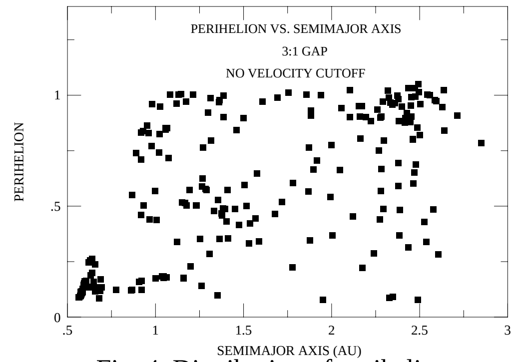

Fig. 4. Distribution of perihelion vs. semimajor axis for the same set of grazing impacts.

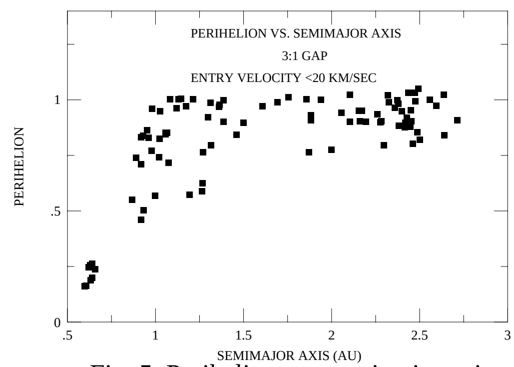

Fig. 5. Perihelion vs. semimajor axis for atmospheric entry velocities < 20 km/sec.

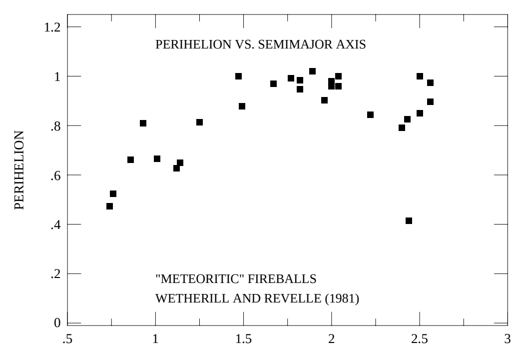

Fig. 6. Perihelion vs. semimajor axis for recovered fireballs and similar fireballs inferred to be stony meteorites (11).